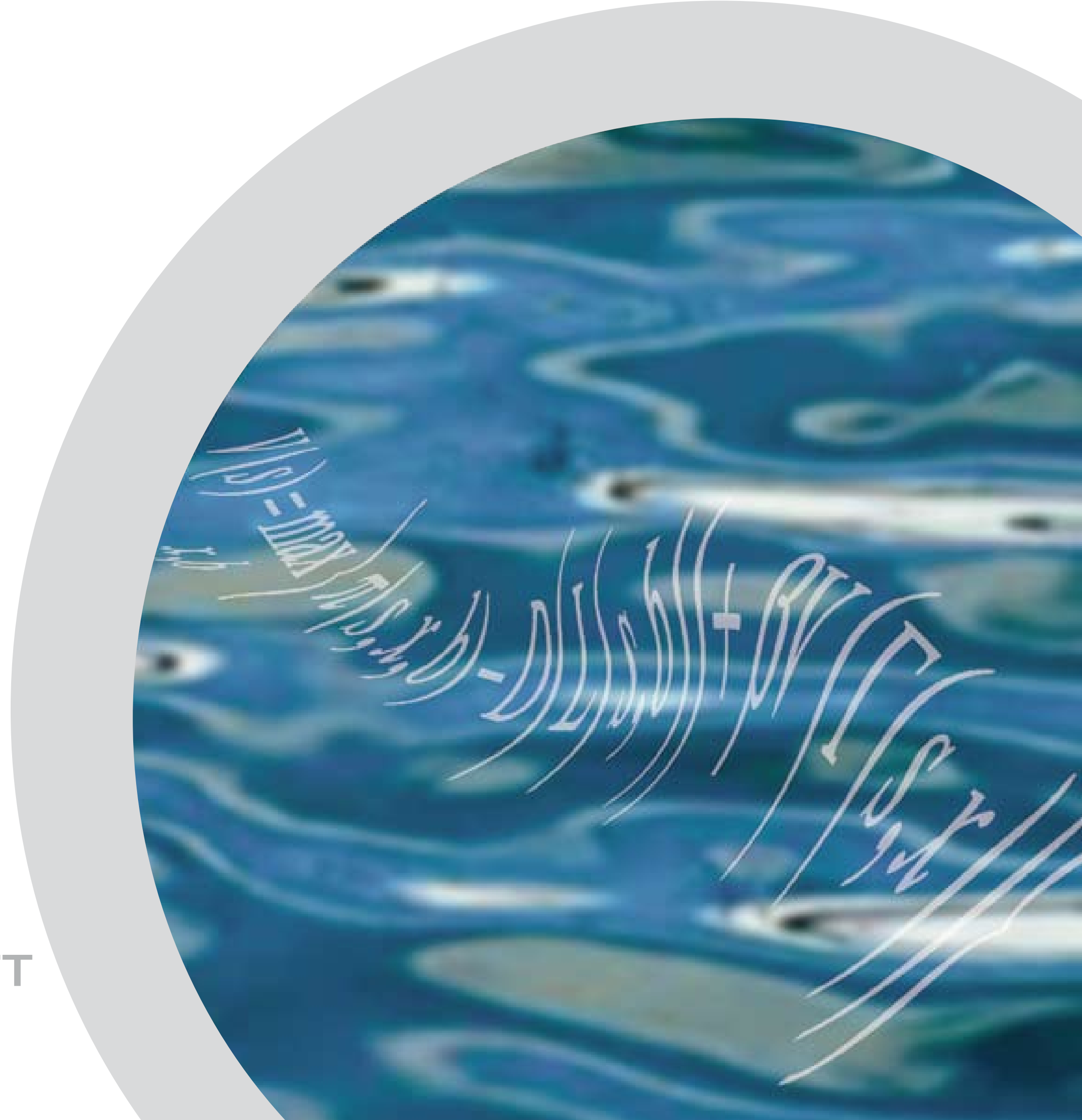
MTT SCIENCE 13

Essays on socially optimal phosphorus policies in crop production

Doctoral Dissertation

Antti Iho



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Essays on socially optimal phosphorus policies in crop production

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Abstract

Phosphorus is a nutrient needed in crop production. While boosting crop yields it may also accelerate eutrophication in the surface waters receiving the phosphorus runoff.

The privately optimal level of phosphorus use is determined by the input and output prices, and the crop response to phosphorus. Socially optimal use also takes into account the impact of phosphorus runoff on water quality. Increased eutrophication decreases the economic value of surface waters by deteriorating fish stocks, curtailing the potential for recreational activities and by increasing the probabilities of mass algae blooms.

In this dissertation, the optimal use of phosphorus is modelled as a dynamic optimization problem. The potentially plant available phosphorus accumulated in soil is treated as a dynamic state variable, the control variable being the annual phosphorus fertilization. For crop response to phosphorus, the state variable is more important than the annual fertilization. The level of this state variable is also a key determinant of the runoff of dissolved, reactive phosphorus. Also the loss of particulate phosphorus due to erosion is considered in the thesis, as well as its mitigation by constructing vegetative buffers.

The dynamic model is applied for cereal production on clay soils. At the steady state, the analysis focuses on the effects of prices, damage parameterization, discount rate and soil phosphorus carryover capacity on optimal steady state phosphorus use. The economic instruments needed to sustain the social optimum are also analyzed. According to the results the economic incentives should be conditioned on soil phosphorus values directly, rather than on annual phosphorus applications. The results also emphasize the substantial effects the differences in varying discount rates of the farmer and the social planner have on optimal instruments.

The thesis analyzes the optimal soil phosphorus paths from its alternative initial levels. It also examines how erosion susceptibility of a parcel affects these optimal paths. The results underline the significance of the prevailing soil phosphorus status on optimal fertilization levels. With very high initial soil phosphorus levels, both the privately and socially optimal phosphorus application levels are close to zero as the state variable is driven towards its steady state. The soil phosphorus processes are slow. Therefore, depleting high phosphorus soils may take decades.

The thesis also presents a methodologically interesting phenomenon in problems of maximizing the flow of discounted payoffs. When both the benefits and damages are related to the same state variable, the steady state solution may have an interesting property, under very general conditions: The tail of the payoffs of the privately optimal path – as well as the steady state – may provide a higher social welfare than the respective tail of the socially optimal path. The result is formalized and applied to the created framework of optimal phosphorus use.

Key words:
Phosphorus fertilization, soil phosphorus, phosphorus runoff, dynamic programming

Esseitä yhteiskunnallisesti optimaalisesta fosforinkäytöstä viljanviljelyssä

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Tiivistelmä

Fosfori on kasvintuotannon kannalta välttämätön ravinne. Se lisää satoja mutta tuotantoalueen alapuolisissa vesistöissä sen huuhtoutuminen voi kiihdyttää rehevöitymistä.

Yksityistaloudellisesti järkevä fosforinkäytön taso määräytyy fosforin hinnan, sen satovaikutuksen ja lopputuotteen hinnan perusteella. Yhteiskunnallisesti järkevää tasoa määriteltäessä tulee tämän lisäksi ottaa huomioon fosforihuuhtoumien vaikutus rehevöitymiseen ja sen kielteiset hyvinvointivaikutukset kuten heikentyneet virkistyskäyttömahdollisuudet, kalakantojen muutokset ja massaleväkukintojen todennäköisyyksien kasvaminen.

Tässä väitöskirjassa luodaan viitekehys fosforinkäytön järkevän tason määrittelemiseen niin yksityis- kuin yhteiskuntataloudelliselta kannalta. Luodun mallin tilamuuttujana on maaperään kertynyt, kasveille potentiaalisesti käyttökelpoinen fosforivaranto, jonka tasoa voidaan hitaasti ohjata vuotuisella fosforilannoituksella. Tämä maaperän fosfori on sadon kannalta varsinaista fosforilannoitusta merkittävämpi komponentti. Liukoisen, välittömästi kasveille käyttökelpoisen fosforin huuhtouma on niinikään sidoksissa tähän fosforivarantoon. Mallilla ratkaistaan myös, kuinka eroosioherkkyydestä riippuvan hiukkasmaisen fosforin joutumista vesistöihin tulisi torjua vesistöjen varteen perustettavin suojakaistoin.

Mallia sovelletaan savimailla viljeltävän ohran fosforilannoituksen tarkasteluun. Mallin avulla tarkastellaan hintojen, haitan arvostuksen ja maaperän fosforidynamiikan vaikutuksia järkevään pitkän aikavälin fosforinkäyttöön. Lisäksi analysoidaan optimiratkaisua tukevien taloudellisten ohjauskeinojen asetantaa. Tulosten mukaan ohjauksen kannattaisi perustua suoraan maaperän fosforitasoon vuotuisen lannoitusmäärän asemesta. Toisaalta tulosten mukaan viljelijän ja yhteiskunnan toisistaan poikkeavat diskonttokorot vaikuttavat ohjauskeinojen tasoon merkittävästi.

Työssä selvitetään myös, miten fosforivaranto kannattaa ohjata kohti pitkän aikavälin tasapainoa eri lähtötasoilta lähdettäessä. Samoin selvitetään, miten optimaaliset polut kohti tasapainoa riippuvat tarkasteltavan lohkon eroosioherkkyydestä. Fosforivarannon lähtötason vaikutus optimaalisiin polkuihin on merkittävä. Korkeimmilta lähtötasoilta lähdettäessä optimaaliset polut pyrkivät pudottamaan varantoja erittäin nopeasti kohti tasapainoa. Maaperäprosessit ovat kuitenkin erittäin hitaita ja fosforivarannon köyhdyttäminen voi kestää kymmeniä vuosia.

Tutkimus nostaa esille myös menetelmällisesti mielenkiintoisen ilmiön diskontattujen hyötyjen summan maksimointiin perustuvassa optimointitehtävässä. Kun hyöty ja haitta linkittyvät samaan dynaamiseen tilamuuttujaan, tasapainoratkaisulla voi varsin tavallisten ehtojen vallitessa olla yllättävä ominaisuus: yksityistaloudellisen optimipolun loppuosa – pitkän ajan tasapaino mukaan lukien – voi tietystä ajanhetkestä eteenpäin tuottaa suurempaa yhteiskunnallista hyötyä kuin yhteiskunnallisesti optimaalinen polku. Työssä formalisoidaan tämä ilmiö ja tarkastellaan sen ilmenemistä.

Avainsanat:
Fosforilannoitus, maaperän fosforivaranto, fosforihuuhtouma, dynaaminen ohjelmointi

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I have completed the thesis while working in the Department of Economics and Management at the University of Helsinki, and at the MTT Economic Research. When starting my post graduate studies in 2003, the major subject Environmental Economics was experiencing an extremely dynamic phase. The undergraduate curriculum was constantly developing to meet higher standards, and the number of post graduate students was rapidly increasing. I had the opportunity and the privilege to work in the department during the time. The feeling of making a difference was distinct. I am ever grateful to Professor Markku Ollikainen for having, sharing and working for the dream of a strong major, producing professionals for the field. I also thank Professor Ollikainen for his strong support and guidance during the entire path from first-year undergraduate student until finalizing this thesis.

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List of essays

The thesis is based on the following essays:

I **Iho, A. 2010.** Spatially optimal steady state phosphorus policies in crop production. European Journal of Agricultural Economics 37(2): 187–208.

II **Iho, Antti and Laukkanen, Marita.** Precision Phosphorus Management and Agricultural Phosphorus Loading. Manuscript.

III **Iho, Antti and Kitti, Mitri.** A tail-payoff puzzle in dynamic pollution control. Manuscript.

Reprint of the first essay is published with the permission of Oxford Journals.

Authors' contribution

Antti Iho and Marita Laukkanen jointly planned the research idea of the second essay. Iho was responsible of writing the first drafts of the manuscript, which the authors jointly processed into its final form. The modeling and analysis was jointly conducted by the authors.

The third article was co-authored by Antti Iho and Mitri Kitti. Iho planned the original research idea. Iho was responsible of writing the first drafts of the manuscript, which the authors jointly processed into its final form. The modeling and analysis was jointly conducted by the authors. Kitti was responsible for most of the mathematical proofs.

Contents

1 Phosphorus as an economic problem

Phosphorus is a nutrient required in crop production. In surface waters, however, elevated phosphorus concentrations may have adverse effects on human welfare. Where high levels of phosphorus cause the phytoplankton biomass to increase, this may combine with other eutrophication mechanisms to increase turbidity, heighten the probability of mass algae blooms, reduce biodiversity and introduce toxic substances.

In inland lakes and rivers, phosphorus is most often the limiting nutrient for primary production. Phosphorus losses from agriculture are substantial: their share of anthropogenic phosphorus loads into the Baltic Sea, for instance, is estimated to be as high as 57 percent (Helcom 2004). Phosphorus has a twofold influence on social welfare: It increases welfare by elevating crop production, and decreases it by accelerating eutrophication.

1.1 Perspective: the private farmer

Phosphorus affects crop growth mainly through potentially plant available phosphorus accumulated in soil (hereinafter 'soil phosphorus'). The level of soil phosphorus is gradually determined by annual phosphorus balances, i.e. the differences between phosphorus application and crop uptake. Hence, the farmer's use of phosphorus is best modeled as a dynamic programming problem where amount of phosphorus applied is the control variable and soil phosphorus the state variable.

Consider a farmer maximizing the sum of discounted per period profits (*π*) from crop production (*y*) over an infinite time horizon by choosing fertilization (*x*) at each period. Fertilization affects the following period's soil phosphorus (*s*) according to the transition function (Γ), and production is a function of fertilization and soil phosphorus. Normalizing prices to one and assuming other costs to be zero, the problem becomes:

$$\begin{gathered} \max_{x_t} \sum_{t=0}^{\infty} \beta^t \left[y(s_t, x_t) - x_t \right] \\ s.t.\;\; s_{t+1} = \Gamma(s_t, x_t), \end{gathered} \qquad (1)$$

where the discount factor (*β*) is derived from the discount rate (*r*) by the equation $\beta = \frac{1}{1+r}$.

The optimality conditions for (1) are derived from the steady-state Bellman equation:

$$V(s) = \max_{x} \left[\pi(s,x) + \beta V(\Gamma(s,x)) \right], \qquad (2)$$

where *V* represents a value function. At the steady state, the choice and the state variables are unchanged between periods. The optimality conditions consist of a Euler equation and a stationary condition:

$$\begin{gathered} \pi_x(s^*, x^*)(1 - \beta\Gamma_s(s^*, x^*)) \\ + \beta\Gamma_x(s^*, x^*)\pi_s(s^*, x^*) = 0 \end{gathered} \qquad (3)$$

$$\Leftrightarrow \left(y_x - 1 \right) + \beta\Gamma_x \frac{y_s}{(1 - \beta\Gamma_s)} = 0 \qquad (4)$$

$$s^* = \Gamma(s^*, x^*). \qquad (5)$$

At the optimum, the farmer balances the marginal effects of phosphorus fertilization on current period profits ($\pi_x = y_x - 1$) and discounted future profits, the second term in (4). The (imputed) value of a marginal unit of soil phosphorus is $\frac{y_s}{(1-\beta\Gamma_s)}$. It is the sum of an infinite geometric sequence of profits generated by a marginal increase in *s* ($y_s + \beta\Gamma_s y_s + \left(\beta\Gamma_s\right)^2 y_s + \ldots$). This increase, for its part, is generated by the marginal effect of *x* on *s* (Γ_x). The value is realized in the following period and is thus discounted once.

Assuming y_s, y_x, Γ_x, $\Gamma_s > 0$; y_{ss}, $y_{xx} < 0$, the second term in (4) is positive. Therefore, the marginal profits (π_x) must be negative.

1.2 Perspective: the social planner

Phosphorus runoff from agricultural production may deteriorate the water quality of surface waters. Where this is the case, the social planner's task is either to provide a certain level of environmental quality at the least possible cost or to maximize social welfare.

If we assume that farmers are price takers, social welfare can be expressed as a sum of private profits less the monetarized value of environmental damage. The simplest way to formulate the social planner's problem here – welfare maximization over an infinite horizon – is to introduce a term to the private problem (1) representing damage as a flow. Denoting environmental damage by $D(s,x)$, the social planner's problem becomes:

$$\begin{aligned}&\max_{x_t} \sum_{t=0}^{\infty} \beta^t \left[\pi(s_t,x_t) - D(s_t,x_t)\right] \\ &\qquad s.t.\ \ s_{t+1} = \Gamma(s_t,x_t).\end{aligned} \tag{6}$$

Analogously to equation (4), the social planner's optimality condition becomes:

$$\begin{aligned}&\left(y_x - 1 - D_x\right) \\ &+ \beta\Gamma_x \frac{\left(y_s - D_s\right)}{(1-\beta\Gamma_s)} = 0.\end{aligned} \tag{7}$$

Assume that D_x, $D_s \geq 0$. We can trace the effects of introducing the environmental damage function with the following reasoning: First, assume $D_x = 0$ and $D_s > 0$. This would make the second term in (7) smaller than that in (4), with $(y_x - 1)$ then becoming a smaller negative number; that is, y_x would become larger. Given $y_{xx} < 0$, this would lower fertilization at the optimum. Then assume $D_s = 0$ and $D_x > 0$. Again, this would require increasing y_x, i.e. decreasing fertilization. That is, at the socially optimal steady state there will be less fertilizer applied than at the private optimum. Whether more or less fertilizer will be applied in a socially optimal dynamic steady state than in a static private optimum depends on the parameterization of the functions.

The social planner's goal may also be the cost-effectiveness of environmental protection, that is, achieving a given level of environmental quality at the lowest possible cost. Maximizing social welfare implies cost-effectiveness: A policy that maximizes welfare also achieves the associated environmental quality with the least possible costs. If not, it would be possible to increase welfare by lowering costs and maintaining the environmental quality. In this sense, welfare maximization is a stronger concept than cost-effectiveness. Nevertheless, there are cases and research questions for which cost-effectiveness is a more suitable concept than welfare maximization. Firstly, the social planner might be unable to specify the social damage function. Secondly, one might want to focus the analysis – perhaps an empirical inquiry – on issues such as the efficiency of environmental protection under spatial heterogeneity. In certain circumstances, focusing on cost-effectiveness instead of welfare maximization increases the tractability of the analysis.

To illustrate cost-effectiveness with a simple analysis, suppose that the dynamic element in our phosphorus problem is negligible. The social planner's problem would then be to maximize the welfare of a single period. However, suppose that the damage depends on the sum of phosphorus losses (L) from N parcels with differing runoff characteristics. Further, suppose that the phosphorus loss could be mitigated with active measures, for instance, constructing vegetative filter strips (b) on field edges bordering water bodies. Setting the target level of total phosphorus runoff from N parcels to $\overline{L}$, the social planner's problem could be formulated as:

$$\begin{aligned} &\max_{x_i, b_i} \sum_{i=1}^{N} \pi(x_i, b_i) \\ &s.t. \ \sum_{i=1}^{N} L(x_i, b_i) \le \overline{L}. \end{aligned} \tag{8}$$

Assuming strict equalities and no cross-effects in runoff yields the following first order conditions:

$$\begin{cases} \dfrac{\frac{\partial \pi}{\partial x_i}}{\frac{\partial L}{\partial x_i}} = \dfrac{\frac{\partial \pi}{\partial b_i}}{\frac{\partial L}{\partial b_i}} \\ \sum_{i=1}^{N} L(x_i, b_i) = \overline{L} \end{cases} \tag{9}$$

The upper condition implies that at the cost-efficient solution the ratio of marginal profits and marginal effects on phosphorus loss (i.e. marginal abatement costs) must be equal across all parcels and both measures. Intuitively, this means that the last units of money should be used such that the abatement achieved is equal everywhere, and with both alternative measures. If the last euro spent at parcel *j* would provide smaller effects on phosphorus loss than at parcel *k*, it should be spent at *k* instead of *j*. The lower condition guarantees that the constraint on total phosphorus loss is satisfied.

In practice, the need to vary phosphorus application levels and the construction of vegetative filter strips across parcels depends on the heterogeneity of the target region. For example, if there are substantial differences in erosion susceptibility, strips will probably be concentrated on the parcels most susceptible to erosion. If, on the other hand, parcels are homogeneous, the optimal allocation of strips will be identical everywhere.

2 Literature review

2.1 Phosphorus in crop production

In broad terms, there are two alternative ways to model crop response to nutrient inputs. A linear response and plateau (LRP) model assumes that crop response is linear with respect to the limiting nutrient. Increasing the supply of that nutrient increases the crop yield linearly until some other nutrient becomes limiting. After this point, adding the nutrient does not increase the crop yield (see, e.g., Grimm et al. 1987). An alternative way is to estimate the response as a smooth concave function (see, e.g., Hurley et al. 2004). This approach allows for substitution between nutrients. The analysis by Berck and Helfand (1990) shows that these two approaches are not necessarily conflicting ones. In fact, using LRP functions but allowing for heterogeneity in input use makes it possible to estimate the aggregate-level response as a concave function. Given this bridge between the approaches and the analytical convenience of concave response functions, the use of these functions in aggregate-level policy analysis seems well motivated. For example, Myyrä et al. (2007) estimate the responses to both soil phosphorus and phosphorus application using a concave response function.

2.2 Phosphorus runoff

The water-soluble forms of phosphorus in soil may end up in runoff waters in the form of dissolved phosphorus (DP). They can also be sorbed back into soil constituents, after which they are classified as insoluble. Insoluble phosphorus may be carried into receiving waters with erosion, for example, when soil particles are detached from fields. This type of phosphorus in runoff is called particulate phosphorus (PP).

DP contributes directly to the phosphorus concentration of the receiving water body, where it is eventually assimilated as biotic phosphorus or sorbed into sediments. DP loss is strongly correlated with the level of soil phosphorus (McDowell and Sharpley 2001; Vadas et al. 2005; Ekholm et al. 2005). Schroeder et al. (2004) list the studies examining the relationship between soil phosphorus and DP loss in runoff.[1]

PP, on the other hand, must be desorbed before it becomes available for primary production in receiving waters. As some PP is deposited into sediments before desorption, only a proportion of total PP can be regarded as potentially bioavailable (see, e.g., Ekholm 1998; Uusitalo et al. 2003).

The determinants of PP loss are mainly those governing erosion: the amount and timing of rainfall, soil type, stability of soil structure, cultivation technology, and crop choice. Field slope is a central determinant of erosion (Wischmeier and Smith 1978). Eventual PP loss is determined by the total phosphorus concentration of soil lost with eroded particles.

Vegetative filter strips are often used to reduce the risk of erosion and filter nutrients from surface runoff (see Dosskey 2002 for a review of studies on the abatement effects of filter strips). The strips mainly filter PP from surface runoff. Their effect on DP loss is ambiguous: they have been found to decrease it (Schmitt et al. 1999; Lee et al. 2000) and to increase it (Uusi-Kämppä and Kilpinen 2000). Dillaha et al. (1989) find increasing effects in some individual experiments, decreasing in others. A simple way to reduce DP loss is to lower the soil phosphorus level. The two major differences between these two ways to mitigate phosphorus loss is that lowering soil phosphorus is more time consuming than constructing filter strips and that mitigating erosion primarily reduces the loss of particulate phosphorus, the environmental damage attributable to which is smaller than its share in total phosphorus loss (in kilograms) indicates.

Not only the load from pollution sources, but also the retention of phosphorus affects efficient phosphorus policies. Retention is usually defined as the difference between the phosphorus input to the lake (or other water body) and output from the lake. The mass balance models find the retention of total phosphorus to be correlated with, for instance, the phosphorus concentration, and the volume, the mean depth and the water renewal time of the lake (see, e.g., Vollenweider 1975; Frisk 1981). Frisk (1989) emphasizes that the retention models are lake-specific and not universal.

Quantifying phosphorus retention is difficult. Firstly, the material balance models need to be empirically specified for each lake. Secondly, it seems that most retention models available in literature focus on total phosphorus concentrations. In economic models, however, it is justified to use algal-available phosphorus as a state varia-

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[1] Naturally, soil phosphorus is not the only factor influencing DP loss. By modeling DP loss as a function of soil phosphorus only, one neglects, for instance, the influence of soil-to-solution ratios and the amount and the saturation rate of oxides in soil (see, e.g., Sharpley et al. 1981 and Yli-Halla et al. 1995). However, soil phosphorus is a readily available measure.

ble. It is driving eutrophication and hence the economic losses related to phosphorus runoff. It's share of total phosphorus is small (see, e.g., Frisk 1989; Uusitalo et al. 2003). Furthermore, the sediment processes driving the binding and release of phosphates are extremely complicated (see, e.g., Lehtoranta et al. 2008). Scarcity of data needed to model individual basins would make the task even more complicated.

On a general level, the economics of regional pollution control are well understood and documented in environmental economic literature (see, e.g., Xepapadeas 1997, pp 55–56). Phosphorus runoff occuring from sources near the recipient should be treated more harshly than those in far distance, given that one takes into account only the environmental quality at the receiving water body. Analytically, this would mean adding an individual transport coefficient for each parcel in conditions (9), describing the share of pollution eventually entering the receptor. In this case, optimality conditions would require that costs from an incremental increase in abatement *at the receptor point* are identical across all parcels/pollution sources.

To keep the analyses tractable, all articles in this thesis ignore the effect of phosphorus retention. If spatial data regarding retention were available, it would be justified to use it when giving targeted policy recommendations for a given lake or reservoir. Here, however, it can be ignored without loss of generality.

2.3 Damage from eutrophication

There are two central aspects of the economic damage from eutrophication of surface waters due to external phosphorus (or nitrogen) loads. Firstly, the biological process of eutrophication exhibits nonconvexities, mainly due to potential internal phosphorus loads. Assume, for instance, that an increase in external phosphorus loads by a ton per year increases the level of eutrophication by a certain amount. Nonconvexity in eutrophication would mean that reducing the external load back to its original level would not bring the eutrophication to its original level. Bringing the water body back to its initial state would require reducing external loads by *more* than a ton per year. The economics of such a dynamic system, often linked to shallow lakes, have been described in the seminal article by Mäler et al. (2003). In a short period of time, the article has inspired an entire thread of literature related to nonconvexities of dynamic systems and their implications for economic decision making.

Secondly, it is often assumed that the disutility from eutrophication increases the faster the higher the level of eutrophication. That is, the damage function is assumed to be convex. To illustrate, assume that Secchi depth, which indicates the turbidity of water, were the indicator (fully) correlated with the negative effects of eutrophication. It is rather intuitive to assume that people would be willing to pay more for an increase in Secchi depth from one meter to two than for an increase from ten meters to eleven.

On balance, the external phosphorus load has a different value of disutility depending on the status of the hydrological system receiving the pollution and people's willingness to pay for a particular environmental state of the system. However, one is able to incorporate these features in the economic analysis only if one considers all sources of external phosphorus in the (dynamic) optimization model. Of course, one must also be able to describe the hydrological development of the system with regard to both internal and external phosphorus loads. If one wants to analyze a single industry that is polluting a water body receiving pollution from other, multiple anthropogenic sources, the only feasible damage function is a linear approximation that links the units of external phosphorus load with a constant monetary value. [2]

2.4 Optimal phosphorus policies

Griffin and Bromley (1982) developed a conceptual framework describing the regulation of agricultural pollution. Their key contribution was to overcome the challenges posed by the unobservability of nonpoint pollution, or, rather, the difficulty of linking it with its source, which impedes the direct use of instruments suitable for observable point-source loads. Griffin and Bromley (1982) showed that the first-best solution can be achieved by using a continuously differentiable pollution production function. This enables the regulator to use the traditional set of instruments. They also examined whether control should focus on the farmer's actions or on the resulting nonpoint pollution using two regulatory approaches: incentives and quantity restrictions. Hence, they analyzed four different policy options, examples of which include: 1) taxing estimated nutrient runoff, 2) setting standards for nutrient runoff, 3) taxing fertilization and 4) setting fertilization limits. They concluded that alternative policies can be applied equally efficiently if properly combined with the pollution production function.[3]

This result was challenged by Shortle and Dunn (1986), who argued that the stochasticity of nonpoint pollution, as well as information asymmetries between the regulator and the farmer, influence the efficiency of alternative instruments. Acknowledging these, they found that incentivizing management practices (e.g., taxing fertilization) is generally more favorable than the other three policy alternatives. Braden and Segerson (1993) list the basic properties of any instrument or variable upon which an instrument is based. Firstly, instruments should reflect the environmental conditions as accurately as possible. For instance, if the level of accumulated soil phosphorus correlates more strongly with phosphorus runoff than do annual phosphorus fertilization levels, it would be a better basis for a policy instrument. Secondly, the instruments should be enforceable on both the practical and political levels. Thirdly, they should be spatially and temporally targetable.

Griffin and Bromley (1982) also touched upon the temporal aspects of agricultural policies. They noted that differences in discount rates of the private farmer and the social planner generate a temporal externality. Because the choice of phosphorus fertilization is a dynamic programming problem, this externality will affect the differences between privately and socially optimal phosphorus uses. To our knowledge, however, this issue has not been analyzed in the literature, although the dynamic character of phosphorus in agriculture has received attention. Schnitkey and Miranda (1993) analyze the optimal use of manure

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[2] Consider pollution originating from multiple sources and the environmental damage at the receptor being convex. It is obvious that focusing on a single source of pollution while keeping others fixed – i.e. equating its marginal abatement costs with marginal damage – yields higher abatement requirements for that source than would be the case under social optimum, where all pollution sources were able to abate. Only when other sources abate exactly the socially optimal amount, the remaining source can be analyzed separately. Assume that the underlying damage function for, say, the Gulf of Finland would be convex. Maximizing social welfare from agriculture net of its environmental damage *using the parametrized convex damage function* would overestimate the abatement requirements for agriculture. When focusing on a single industry, one must use a linear damage function approximation.

[3] They noted that the number of parameters to be specified for the regulator varied from a single parameter (in the case of nonpoint incentive) to a parameter for each firm and production input (in the case of regulating management practices).

and mineral fertilizer on farms that engage in both animal husbandry and crop production. They show how both the nutrient ratios of manure and its hauling costs affect its optimal application rates. In this light, they go on to analyze how alternative policies would affect production choices and the accumulation of nutrients. In their model, soil phosphorus is linked with crop production but not with phosphorus losses. Goetz and Zilberman (2000) determine spatially and intertemporally optimal phosphorus use (in the form of mineral fertilizers and manure), the optimal number of animal units, and the optimal phosphorus concentration in the receiving body of water. The phosphorus loading potential of the parcels is defined by an index, fixed in time; that is, it does not evolve with the accumulation of soil phosphorus. Goetz and Keusch (2005) include crop rotation and tillage practices in their analysis. In their model, soil loss determines phosphorus loss. The links between soil phosphorus dynamics and losses of dissolved phosphorus are not acknowledged.

Precision agriculture refers to production technology that utilizes information intensively. It may refer to maximizing the utilization of inputs and hence minimizing residual inputs, which are the ultimate cause of agricultural pollution. Boosting utilization requires improving spatial information on, say, the nutrient stocks in and crop uptake of the soil. Understanding the actual need for nutrient inputs for particular locations enables the farmer to target and differentiate fertilization rates between different parcels and even within parcels. However, as Lichtenberg (2002) points out, even if the farmer acquired information on spatial heterogeneity and took it into account when determining his/her nutrient application rates, this would not necessarily increase social welfare. As long as the private farmer does not acknowledge environmental damage, adopting more precise fertilization practices may in fact decrease social welfare. Khanna and Zilberman (1997) provide an interesting insight into precision technologies. They show that even though the technologies would be beneficial for private farmers, there are elements impeding their adoption. Firstly, the benefits of adopting such technologies are heterogeneous among farmers. Secondly, institutional elements do not incentivize – and may even discourage – their adoption. Formal analyses of precision agriculture are few and far between (Lichtenberg 2002). The second article in this thesis provides interesting qualitative results in this area of research.

Finally, there are numerous empirical studies on the impact of heterogeneity on optimal policies. Typically, these studies compare the use of either differentiated or uniform instruments to regulate agricultural externalities generated in heterogeneous conditions. Helfand and House (1995) examined the efficiency of uniform regulation on nitrate leaching in lettuce production. Their results suggest that the efficiency losses related to the use of second-best (uniform) regulation are fairly minor (up to 2% of the quasi-rents of production). Similar results were found by Fleming and Adams (1997), who examined controlling nitrates in groundwater. By contrast, Schwabe (2001) found a uniform strategy to reduce nitrogen loads by 30% to be about 70% more costly than the least-cost alternative. These results emphasize that the more spatial differences there are in the production and nonpoint production function, the more is to be gained by using targeted policies.

Lichtenberg (2002) provides an extensive treatment of the optimal use of polluting inputs under heterogeneity. He postulates a model with a continuum of land types and a choice between two alternative crop choices/agricultural practices. The socially optimal and the privately optimal solutions differ with land quality.

Iho (2005) analyzes the cost-effectiveness of water protection measures as the target level of nutrients varies. In practice, environmental targets may be set at very optimistic levels. For instance, the Finnish water protection targets until 2005 established goals for phosphorus and nitrogen reduction of 45% and 40%, respectively (Vesiensuojelun tavoitteet vuoteen 2005 1998). He constructs a scenario in which it is assumed that one could determine the cost-effective allocation of measures to achieve this target and that only an identical fraction (less than one) of each measure would actually be carried out. The analysis, carried out in the context of the European Union Water Framework Directive, indicates how severely such downscaling of efficient allocations vitiates the efficiency of environmental protection.

3 Phosphorus in Finland

3.1 Phosphorus in crop production

Phosphorus has a disputed role in Finnish crop production. Even though the total content of phosphorus in soils may be high, the reserves are poorly available for plants. This is partly due to the high content of aluminum and iron oxides in soils, which form tight chemical bonds with phosphate anions (Kaila 1963a, 1963b).

In mineral soils, the mean total phosphorus content (of topsoil) has increased from 1.8 tons ha^{-1} in the 1930s to its current level of about 3 tons ha^{-1} (Saarela 2002). The application of phosphorus fertilization has not increased linearly over those decades. The average phosphorus surplus was 15 kg ha^{-1} in the 1960s, about 25 kg ha^{-1} in the 1970s and 1980s, and about 10 kg ha^{-1} in the 1990s.[4] There are at least two disputed issues with regard to these application levels. The first is how the surpluses affect the development of potentially plant available soil phosphorus, which is crucial to crop growth. In Finland, soil phosphorus is approximated by the ammonium acid acetate method developed by Vuorinen and Mäkitie (1955).[5] The second is what the crop response to phosphorus fertilization and soil phosphorus is.

In their long-term field trials, Saarela et al. (2004) analyzed crop yields and STP (soil test phosphorus) development as followed by varying phosphorus application rates and initial STP levels. According to their results, maintaining an initial STP level of 12 mg l^{-1} would require an annual phosphorus surplus of about 9 kg ha^{-1}.[6] According to estimates of Ekholm et al. (2005) on identical soils, on the other hand, maintaining an STP level of 12 mg l^{-1} would require an annual surplus of 16.6 kg ha^{-1} – a radically different result. What the two estimates have in common is the implication that maintaining the STP at a given

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[4] The surplus is defined as the difference between the average annual phosphorus fertilization and crop uptake

[5] The result of this soil phosphorus test will be abbreviated hereinafter as STP.

[6] Note that 9 kg ha^{-1} denotes the phosphorus surplus, not the amount of phosphorus applied. With an annual phosphorus uptake of, say, 10 kg ha^{-1}, maintaining the STP level unaltered would require phosphorus fertilization of 19 kg ha^{-1}.

level requires a clear phosphorus surplus. One reason for this is that phosphorus bonds become stronger with time (Kaila 1963b). Another, straightforward reason is that some of the phosphorus is inevitably lost from the system in runoff.

The potentially plant available phosphorus in soil is generally more important for crop growth than the annually applied phosphorus. In Finnish practice, however, the recommendations for phosphorus use are based on the fertilizer's immediate effect on crop yields (see, e.g. Valkama et al. 2009). As shown in the opening section, omitting the transition dynamics of soil phosphorus results in false phosphorus application recommendations. Saarela et al. (1995) discuss optimal phosphorus use with varying STP levels and input and output prices. Their analysis accounts for the development of STP heuristically by discussing the long-term economic effects of altering the STP level – and thereby future profits. To date, the optimal choice of phosphorus has not been presented as a problem of controlling the development of soil phosphorus – a problem entailing a decision between the interdependent processes of crop growth and phosphorus losses. Valkama et al. (2009), for instance, recommend heavy reductions in overall phosphorus fertilization levels based on crop response to phosphorus fertilization. As the quality of surface waters is an extremely relevant issue in the Finnish political debate, and the role of agriculture is central to that issue, it would be important to have a common framework for analyzing the optimal use of phosphorus.

3.2 Phosphorus and environmental regulation

Finland is one of the few countries that have actually implemented a tax on fertilization (Rougoor et al. 2001). The tax, introduced in 1976, was mainly levied for fiscal purposes, but was also designed to decrease the use of fertilization and thereby reduce overproduction (Sumelius 1994). The tax was adjusted several times until 1994, when it was abolished upon Finland's joining the European Union (EU).

In 1989, for instance, a law was enacted that introduced a special phosphorus tax on fertilizers containing more than two percent phosphorus. The tax was to be valid for the year 1990 only. The tax rate was set at 0.5 FIM per kilogram of phosphorus (about 0.08 €) from January to mid-June, and one FIM (about 0.17 €) until the end of the year (Laki fosforilannoiteverosta 1989). In 1990, a similar law was enacted that set the tax rate to one FIM from January to mid-June, and 1.5 FIM (about 0.25 €) until the end of the year (Laki fosforilannoiteverosta 1990). In 1991, the law on phosphorus tax was repealed. However, the phosphorus tax was included in a law on fertilizer taxes (Laki lannoiteverosta annetun lain muuttamisesta 1991). The tax rate was set to 1.7 FIM (about 0.28 €) per kilogram of phosphorus. In light of the minor crop response to phosphorus fertilization as compared to the response to accumulated soil phosphorus, it seems obvious that a tax rate with such myopic fluctuations would not have the desired – or any – effects on phosphorus losses from agriculture.

Phosphorus regulation changed dramatically when Finland joined the EU and its common agricultural policy. The regulation was set out in the subsequent environmental programs (1995–1999, 2000–2006 and 2007–2013), which essentially applied three ways to mitigate phosphorus losses: 1) constraints on mineral fertilizers, 2) constraints on the use of manure, and 3) special subsidies for various measures to mitigate phosphorus losses. To be eligible for an environmental subsidy, a farmer has to fulfill certain conditions regarding environmentally sound production, which include the three constraints mentioned above. In addition, the programs grant special subsidies for measures such as constructing artificial wetlands. Palva et al. (2001) and Mattila et al. (2007) have assessed the effects of agri-environmental regulation on water pollution during the periods 1995–1999 and 2003–2005, respectively. To our knowledge, however, there has been no comprehensive assessment focusing specifically on phosphorus regulation during the program periods.

4 Summaries and main results of the studies

This thesis consists of three studies, each analyzing optimal phosphorus use from different perspectives. The following sections provide brief summaries of the research. Each article is an independent entity and includes a brief, focused literature review. Accordingly, the summaries do not provide references to the relevant literature, although some references are given for narrative purposes, particularly in the case of the third article.

4.1 Iho, A. Spatially optimal steady-state phosphorus policies in crop production

The first study establishes the basic framework informing the research for the thesis. It postulates that the use of phosphorus is a dynamic programming problem that affects private profits and phosphorus runoff by gradually adjusting the level of soil phosphorus. Hence, optimal use is determined by not only the input and output prices and the production function, but also the transition process of soil phosphorus. This approach is particularly appealing, as the runoff of dissolved phosphorus – which is readily bioavailable and may thus contribute to eutrophication directly – can be largely explained by soil phosphorus concentrations.

The model elaborated in the study includes a spatial element to account for the particulate phosphorus lost with eroded soil particles. As susceptibility to erosion varies greatly between field parcels, efforts to control erosion should vary accordingly. The model simultaneously solves for the optimal steady-state levels of phosphorus fertilization and the intensity of erosion control measures when susceptibility varies. Vegetative filter strips are used as a representative measure.

The paper solves the privately and socially optimal use of phosphorus and the desirability of constructing vegetative filter strips. It also examines optimal Pigouvian taxes that would incentivize the private farmer to undertake socially optimal actions. In particular, the paper compares two alternative variables that can be used as determinants of the tax: The tax may be imposed on either soil phosphorus or annual phosphorus fertilization. It is shown that the tax can be imposed equally well on either variable; the outcomes are identical. Interestingly, however, differences in outcomes emerge if there are information problems affecting the parameterization of the transition function. If the social planner fails to estimate the parameters of the transition function correctly, only the tax imposed on soil phosphorus provides the desired outcome in terms of the target level of phosphorus runoff.

The study also presents a rather peculiar result regarding privately and socially optimal steady-state phosphorus levels. If the social planner applies a lower discount rate than the private farmer, the optimal solutions of the two decision makers get closer to each other. In fact, the research demonstrates that there is a threshold level in the difference between the discount rates applied after which the private optimum produces a lower annual load of dissolved phosphorus than the social optimum.[7]

The results have three key policy implications. Firstly, the social planner could impose the regulation directly on soil phosphorus levels. Controlling the actual use of fertilizers serves the environment only by controlling the level of soil phosphorus. Therefore, if aiming for a particular dissolved phosphorus load, the regulator could ignore the transition process and control soil phosphorus directly. Of course, there are informational constraints in observing the level of soil phosphorus. However, as the key determinant of phosphorus load is soil phosphorus, the same constraints exist when regulating the use of fertilizers. Secondly, the results recommend heavy differentiation of erosion control measures. As intuition would suggest, they should be used on fields most susceptible to erosion. Thirdly, the social planner should be careful in setting the abatement targets for cereal production areas: He or she should first determine the desired level of production of both crops and pollution. If (projected) pollution levels are above those desired, one should restrict the use of phosphorus. However, the greater impatience of farmers may have resulted in phosphorus application levels *below* the social optimum. In this case, increasing the use of fertilization would improve welfare.

What the study does not analyze is how the results would change if we were to examine the entire path from various initial soil phosphorus levels towards the socially optimal steady state. The parameterization of the transition function shows that the transition process is very slow in both directions. The second study in the thesis analyzes how this affects the optimal use of phosphorus.

4.2 Iho, A. and Laukkanen, M. Precision phosphorus management and agricultural phosphorus loading

The second study focuses on optimal paths of phosphorus use as a function of prevailing soil phosphorus levels. It departs from steady-state analysis and poses the following questions: What are the optimal phosphorus application levels if we are not at the steady state? How fast are high (low) soil phosphorus levels optimally depleted (accumulated)? How do the paths of the private farmer and the social planner differ, and what are the welfare implications of altering the private decision maker's behavior?

As the loss of dissolved, readily algal available phosphorus is directly linked to the level of soil phosphorus, it is of utmost importance to analyze how field parcels with unnecessarily high soil phosphorus levels should be depleted. There are two main reasons why high soil phosphorus areas emerge in the first place. Firstly, animal husbandry tends to accumulate phosphorus particularly on parcels close to the farm center, as modeled by Schnitkey and Miranda (1993). Secondly, certain crops require a very high soil phosphorus status, examples being sugar beet and potato. At the European Union level, the acreages of sugar beet have been declining dramatically in recent years (Eurostat 2009). It would be important to know the optimal way to deplete the soil phosphorus

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[7] The third study presents oddities of steady-state solutions with identical discount rates.

from such fields. A comprehensive strategy to this end would examine how sensitive the optimal fertilization policy is to the prevailing phosphorus status, how long it takes to deplete or accumulate soil phosphorus, and what the implications of this are for total phosphorus losses.

The study first approximates the value function numerically and thereafter the optimal policy functions for phosphorus applications and vegetative filter strip use, both as functions of soil phosphorus. It also simulates optimal time paths and compares the welfare effects of alternative policies.

The research produced three main results. Firstly, it demonstrates how strongly the use of phosphorus is differentiated in terms of soil phosphorus. Secondly, it reveals how slight the effect of soil phosphorus is on the optimal use of VFSs (vegetative filter strips). Thirdly, and most importantly, it shows that the higher the initial soil phosphorus levels are, the closer the optimal depletion paths of the private agent and the social planner get to each other. In other words, the results suggest that when the initial reason for sustaining high soil phosphorus disappears (e.g., if the crop planted changes from sugar beet to grain or if a technical innovation is found that substantially decreases the hauling costs of manure), it may not be worthwhile to actively regulate the depletion process. For the first few decades, the depletion paths virtually coincide, even though the private farmer would not take environmental damage into account in his/her optimization problem.

The results suggest that farmer extension might be a good way to sustain the socially optimal depletion processes. As the soil phosphorus transition processes are complicated and perhaps not well known to farmers, it might be enough to simply educate them to maximize their own profits through informed use of phosphorus.

The study also indicates that promoting precision agriculture might be a promising way to restrain phosphorus loads. The term “precision agriculture” refers to agricultural practices which are strongly differentiated by parcel and even within a single parcel. One implication of the findings here is that it might be worthwhile to invest in technology that allows the farmer to carefully trace the soil phosphorus levels in his/her fields. One solution in this regard might be to subsidize the necessary technology.

4.3 Iho, A. and Kitti, M. A tail-payoff puzzle in dynamic pollution control

Whereas the first two studies applied existing methodologies to analyze phosphorus regulation in crop production, the third article is a comment on the methodology itself. It presents a puzzle related to the dynamic programming framework, one detectable in its standard steady-state solution.

The research draws on and contributes to the dynamic pollution control literature. This branch of literature is mostly concerned with stock character of pollution and its implications for dynamically optimal policies. A seminal article is Keeler et al. (1971), who use a simple macroeconomic model to examine how the co-existence of an accumulating pollutant changes the social welfare at the steady state. A policy taking the pollutant into account leads to “*golden age equilibrium*”, whereas a policy ignoring the pollutant leads to “*murky age equilibrium*”. As expected, the social welfare associated with the former is higher. However, the authors note: “In other situations this ordering could be reversed”. They thus suggest that the steady-state outcomes of socially optimal policies might be outperformed socially by privately optimal policies. However, they do not discuss the issue any further.

We present and formalize a similar phenomenon, which we call the tail-payoff puzzle. It refers to a situation where the socially optimal steady-state solution is associated with lower social welfare than the privately optimal steady state solution. This can happen if the environmental damage is due to accumulated capital that also generates private profits. This is exactly the same case as those investigated in studies one and two, where soil phosphorus was the (main) source of private benefits and environmental damage. In the numerical application, we use the example of controlling the loading of dissolved phosphorus from agriculture.

In part, the phenomenon is related to the literature on intergenerational welfare. The fact that discounting treats different generations unequally has given rise to other welfare criteria for assessing policies that affect the welfare of many generations (see, e.g. Chichilnisky (1996) and Asheim et al. (2001)). There are various rules on resource use to satisfy given criteria. For instance, a constant per capita consumption consistent with Rawls's maximin criterion can be achieved by keeping the level of investments equal to rents from exhaustible resource depletion (Hartwick 1977; Rawls 1971; Solow 1974).

The main contribution of the article is to elucidate a little-studied topic in the literature on intergenerational welfare. The tail-payoff puzzle suggests that alternative criteria for welfare maximization might be required even in a very simple model of pollution. The puzzle is presented in the context of flow pollution, but it is straightforward to show that it does not disappear if we allow the pollutant to have a stock character. However, investigating a pollutant with a stock character would affect the limits of discount rates beyond those which the puzzle covers. The necessary condition for the puzzle to occur is that pollution be generated (at least to some extent) directly from the accumulated capital.

5 Discussion and Conclusions

Phosphorus is a major cause of eutrophication in most inland waters and also in many marine watersheds. Often, agriculture is a key anthropogenic source of external nutrient loads. In addition to the complications common to regulation of any type of nonpoint pollution, there are features specific to phosphorus loss that make it an especially challenging phenomenon. Despite the compelling need, the agri-environmental literature has produced few applications regulating phosphorus losses from agriculture. This thesis is an effort to shed light on the salient characteristics of phosphorus in this regard, and on their implications for optimal regulation of phosphorus losses from agriculture.

All the complexities of nonpoint pollution are present in the case of controlling phosphorus loads from agriculture. To keep the analysis tractable and focused on the characteristics of phosphorus, the three component studies of the thesis examine a world under certainty and complete information. This said, the first two essays also discuss the implications for regulation in a world of uncertainty.

The main contribution of the thesis is a transparent and clear-cut dynamic framework for analyzing phosphorus loads from crop production. Here, the distinction between dissolved and particulate forms of phosphorus is essential, for the differences in their role in any environmental damage are substantial. It is evident that, keeping the acreage under agricultural production fixed, the abatement of dissolved phosphorus can be mainly accomplished by altering the level of potentially plant available soil phosphorus reserves accumulated in the soil. This process is very slow. Therefore, in many areas it may be impossible to achieve fast reductions in phosphorus losses from agriculture.

The three main implications of the thesis for the regulation of phosphorus losses are: 1) The focus of regulation should be on soil phosphorus instead of annual phosphorus applications, 2) there is a strong dependence between the optimal phosphorus application and the current soil phosphorus level, and 3) there is a strong dependence of erosion control measures on erosion susceptibility and the opportunity costs of land, and a weak dependence on soil phosphorus levels. The results of study two suggest that where depletion of excessively high phosphorus soils is concerned, precision agriculture might prove to be socially beneficial. The higher the initial soil phosphorus levels, the closer the socially and privately optimal depletion paths become. Of course, if the root cause of excessively high soil phosphorus levels is not eliminated, the privately and socially optimal solutions will differ markedly. This might be the case in, say, regulating the use of manure from animal husbandry.

The issues examined in the third study raise questions on the appropriate foundations for analyzing environmental pollution generated by accumulated production capital. The tail-payoff puzzle detected suggests that socially optimal policies based on discounting the net benefits of production lead to equilibrium outcomes inconsistent with the applied social benefit function. The implications of this finding for policy design are not completely clear. The first study showed that the higher impatience of the private farmer may lead to smaller amounts of accumulated, polluting production capital and therefore to a socially optimal outcome even without regulation. The third article showed that evaluating the steady-state outcomes with a per period social welfare function may prove that the privately optimal steady state solution is socially preferable to the socially optimal solution.

There are numerous ways to extend the analyses conducted. The most obvious would be to include uncertainty in crop yields, input and output prices and environmental effects and to acknowledging the stock effects of phosphorus pollution. Two less obvious ones would be to apply soil phosphorus heterogeneity in the context of precision agriculture. Is there money on the table in crop production on parcels with *on average* appropriate soil phosphorus levels? Put differently, what is the threshold level of spatial heterogeneity in accumulated soil phosphorus that makes it socially worthwhile for the farmer to engage in targeted input use? What kind of instruments would be needed to incentivize farmers to make the needed investments?

Another line of research would be to integrate the dynamic framework used here with the framework for optimal manure and mineral fertilizer applications elaborated by Schnitkey and Miranda (1993). There are various kinds of investments that alter their setting, for instance, those that decrease hauling costs (e.g., removing water from manure) and those that increase the number of midpoints for the critical radius of manure application (e.g., storing manure in multiple locations). Analyzing the social profitability of these investments would require a framework that describes the time paths of soil phosphorus and hence pollution loads.

Certain reservations are in order as regards the seemingly exact numerical results in any of the studies. The parameterizations of the crop response and the transition functions are vitally important in determining the absolute amounts of dynamically optimal phosphorus use. Both parameterizations originate from a single empirical study (Saarela et al. 1995). It would be important to have alternative formulations to test the robustness of the results with regard to these key elements. Moreover, the phosphorus abatement functions of vegetative filter strips are optimistic at the very least. One should consider them a representative measure of erosion control sooner than realistic descriptions of actual filter strip abatement. The main results of the analyses, however, are robust regardless of these parameterizations.

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